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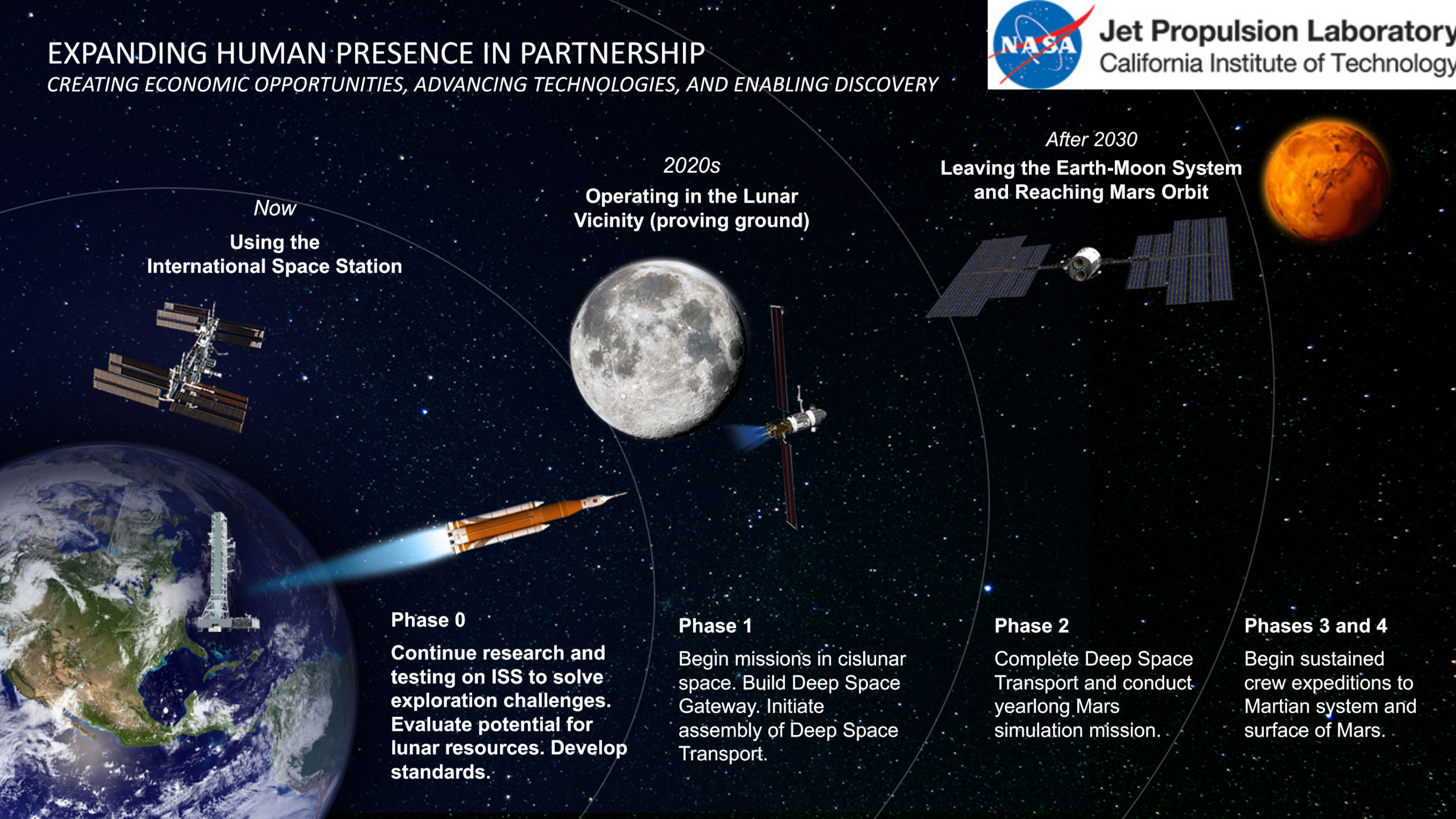
California Institute of Technology

Deep Space Quantum Optics

Makan Mohageg
Quantum Sciences and Technology Group
Communication Architectures and Research Section
Jet Propulsion Laboratory, California Institute of Technology

Outline

- Summary of the LOP-G Mission
- Quantum Optics and General Relativity science goals enabled by LOP-G
- System model for Deep Space Quantum Optical Links


EXPANDING HUMAN PRESENCE IN PARTNERSHIP
CREATING ECONOMIC OPPORTUNITIES, ADVANCING TECHNOLOGIES, AND ENABLING DISCOVERY
NASA
Jet Propulsion Laboratory
California Institute of Technology
Now
Using the International Space Station
2020s
Operating in the Lunar Vicinity (proving ground)
After 2030
Leaving the Earth-Moon System and Reaching Mars Orbit
Phase 0
Continue research and testing on ISS to solve exploration challenges. Evaluate potential for lunar resources. Develop standards.
Phase 1
Begin missions in cislunar space. Build Deep Space Gateway. Initiate assembly of Deep Space Transport.
Phase 2
Complete Deep Space Transport and conduct yearlong Mars simulation mission.
Phases 3 and 4
Begin sustained crew expeditions to Martian system and surface of Mars.

Phase 1 Plan

Establishing deep-space leadership and preparing for Deep Space Transport development

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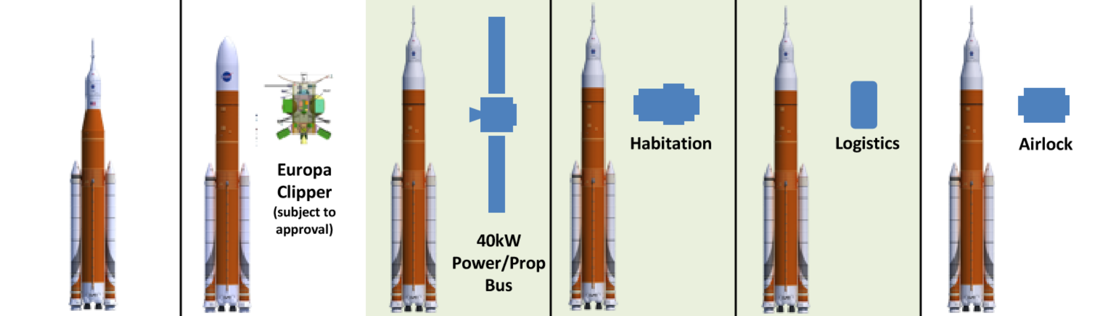
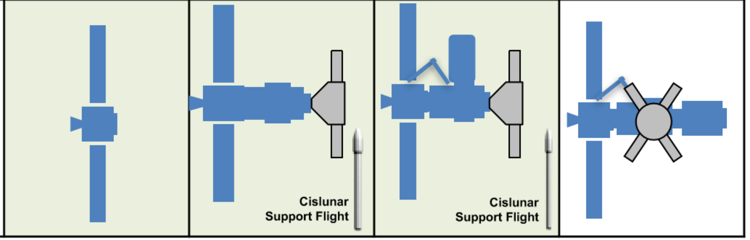
		Deep Space Gateway Buildup			
EM-1	**Europa Clipper**	**EM-2**	**EM-3**	**EM-4**	**EM-5**
2019 - 2025					**2026**
SLS Block 1 Crew: 0	SLS Block 1B Cargo Europa Clipper (subject to approval)	SLS Block 1B Crew: 4 CMP Capability: 8-9T 40kW Power/Prop Bus	SLS Block 1B Crew: 4 CMP Capability: 10mT Habitation	SLS Block 1B Crew: 4 CMP Capability: 10mT Logistics	SLS Block 1B Crew: 4 CPL Capability: 10mT Airlock
Distant Retrograde Orbit (DRO) 26-40 days	Jupiter Direct	Multi-TLI Lunar Free Return 8-21 days	Near Rectilinear Halo Orbit (NRHO) 16-26 days	NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days	NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days
Gateway (blue) Configuration (Orion in grey)			Cislunar Support Flight	Cislunar Support Flight	





These essential Gateway elements can support multiple U.S. and international partner objectives in Phase 1 and beyond

Known Parameters:
- Gateway architecture supports Phase 2 and beyond activities
- International and U.S. commercial development of elements and systems
- Gateway will translate uncrewed between cislunar orbits
- Ability to support science objectives in cislunar space

Open Opportunities:
- Order of logistics flights and logistics providers
- Use of logistics modules for available volume
- Ability to support lunar surface missions

(PLANNING REFERENCE) Phase 2 and Phase 3

Looking ahead to the shakedown cruise and the first crewed missions to Mars

Transport Delivery		Transport Shakedown		Mars Transit	
EM-6	EM-7	EM-8	EM-9	EM-10	EM-11
2027		2028 / 2029		2030+	
SLS Block 1B Cargo P/L Capability: 41t TLI	SLS Block 1B Crew: 4 CMP Capability: 10t	SLS Block 1B Cargo P/L Capability: 41t TLI	SLS Block 2 Crew: 4 CMP Capability: 13+t	SLS Block 2 Cargo P/L Capability: 45t TLI	SLS Block 2 Crew: 4 CMP Capability: 13+t
Deep Space Transport	Logistics	DST Logistics & Refueling	Logistics	DST Logistics & Refueling	Logistics
DST checkout in NRHO 191-221 days Cislunar Support Flight		DSG: continued operations in cislunar space DST: shakedown in cislunar space with return to DSG in NRHO 300-400 days Cislunar Support Flight		DSG: continued operations in cislunar space DST: Mars transit and return to DSG in NRHO Cislunar Support Flight	

Reusable Deep Space Transport supports repeated crewed missions to the Mars vicinity

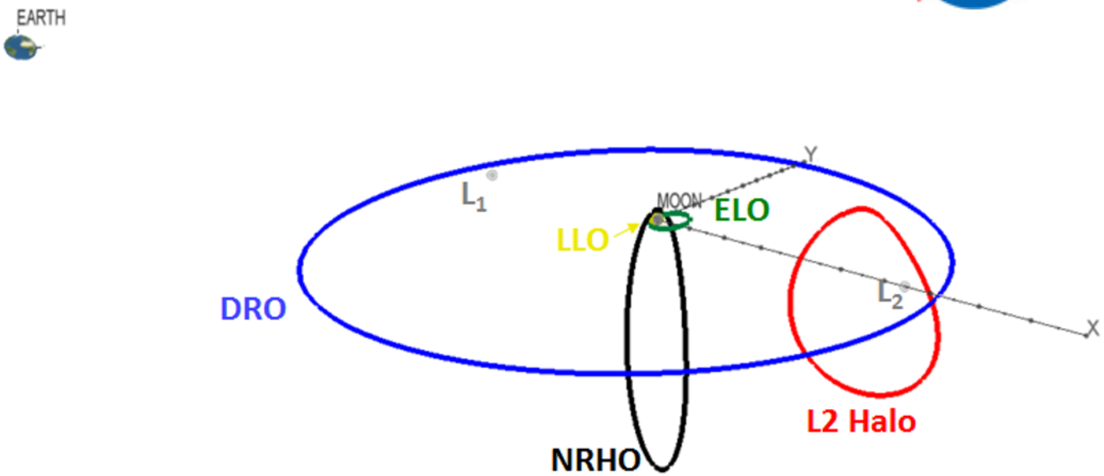
Known Parameters:

- DST launch on one SLS cargo flight
- DST shakedown cruise by 2029
- DST supported by a mix of logistics flights for both shakedown and transit
- Ability to support science objectives in cislunar space

Open Opportunities:

- Order of logistics flights and logistics providers
- Shakedown cruise vehicle configuration and destination/s
- Ability to support lunar surface missions

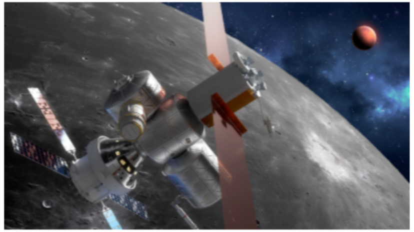
LOP-G Orbit Configurations



Orbit Type		Orbit Period	Lunar (or L-Point) Amplitude Range	Earth-Moon Orientation
Low Lunar Orbit (LLO)	yellow	~2 hrs	100 km	Any inclination
Elliptical Lunar Orbit (ELO)	green	~14 hrs	100 to 10,000 km	Equatorial
Near-Rectilinear Halo Orbit (NRHO)	black	6 to 8 days	2,000 to 75,000 km	Roughly Polar
Earth-Moon L_2 Halo	red	8 to 14 days	0 to 60,000 km (L_2)	Dependent on size
Distant Retrograde Orbit	blue	~14 days	70,000 km	Equatorial

PPE Industry Study Selections

BOEING

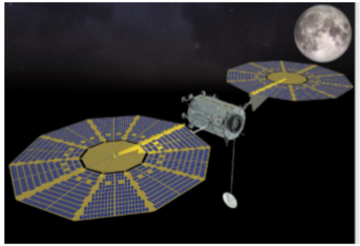


LOCKHEED MARTIN

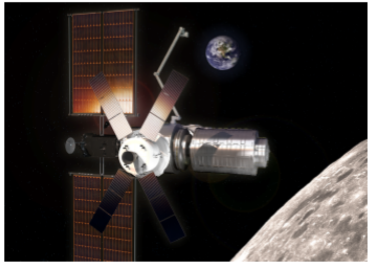
SNC SIERRA NEVADA CORPORATION

AEROJET ROCKETDYNE

DRAPER



Orbital ATK



SSL

DSS Deployable Space Systems

DRAPER

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Programmatic Review of LOP-G

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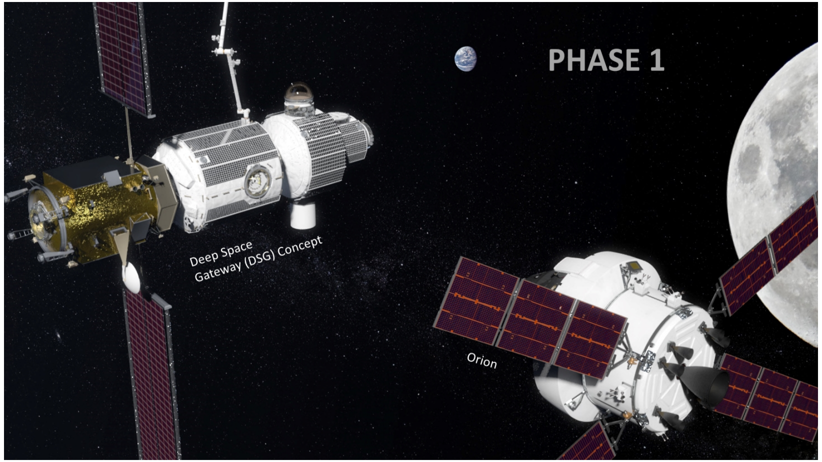
- Proposed >$800M in FY19 budget
  - ISS lifetime cost >$100B
  - Recall “Constellation” mission from GWB era
- How much volume allocated for science?
- What is the balance between different scientific disciplines?
- What is the available spacecraft infrastructure?
- Could BFR developments change the phasing plan?
- When will the AO’s be released?

- First order evaluation of science proposals

Opportunity vs. Opportunistic



SPACE

Scientists pitch for remote human lab

Momentum builds for a crewed outpost around the Moon.

16 | NATURE | VOL 552 | 7 DECEMBER 2017

Fundamental Physics Exploration Enabled by Quantum Optics

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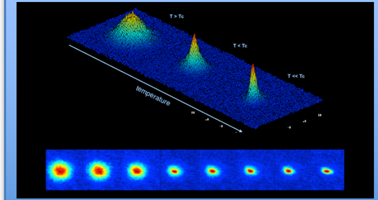
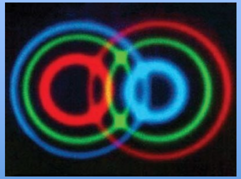
Quantum Theory explains "Atomic Scale" physics



JPL BEC & AI



Quantum Entanglement:
Multiple particles,
one wavefunction

Recent experimental results prove quantum wavefunctions can extend 1000+ km

1

Testing the Bell inequality on frequency-bin entangled photon pairs using time-resolved detection

XIANXIN GUO, YEFENG MEI, AND SHENGWANG DU*

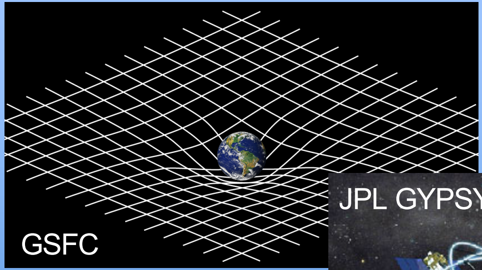
2

Satellite-based entanglement distribution over 1200 kilometers

Juan Yin,[1,2] Yuan Cao,[1,2] Yu-Huai Li,[1,2] Sheng-Kai Liao,[1,2] Liang Zhang,[2,3]

2016 & 2017

Classical Physics/General Relativity explains "Large Scale" physics



Open Questions in Science:

- Does propagation through a changing gravitational potential result in a measurable change to an entangled quantum state?
- If a change in the quantum state is measured, what does that tell us about spacetime?

3

Space QUEST mission proposal: Experimentally testing decoherence due to gravity

ISS Mission proposal (arXiv:1703.08036v2 [quant-ph] 26 Apr 2017)

Quantum Fidelity and Coherence

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Entangled State Production Rate = R pairs/s

Path-A

Path-B

Multiple Measures of Particle A ~ Matrix ρ_1

Multiple Measures of Particle B ~ Matrix ρ_2

R > received flux

Compute Fidelity[7]

$$F(\rho_1, \rho_2) = \left(\mathrm{Tr}\left\{\sqrt{\sqrt{\rho_1}\rho_2\sqrt{\rho_1}}\right\}\right)^2$$

There are formal relationships between coherence and fidelity[8, 9]

Interaction with environment along Path-B drives an *averaging* of the matrix ρ_2

Leading to reduced Fidelity

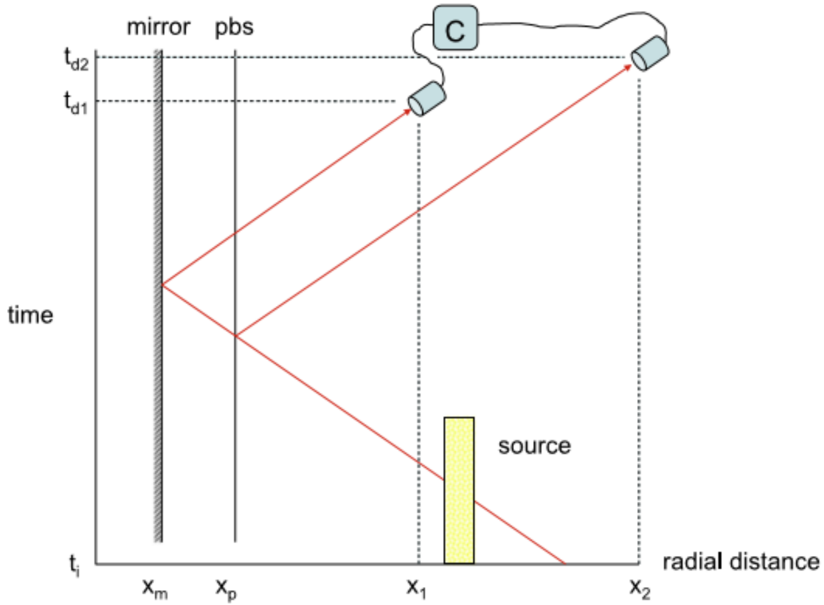
"environment"

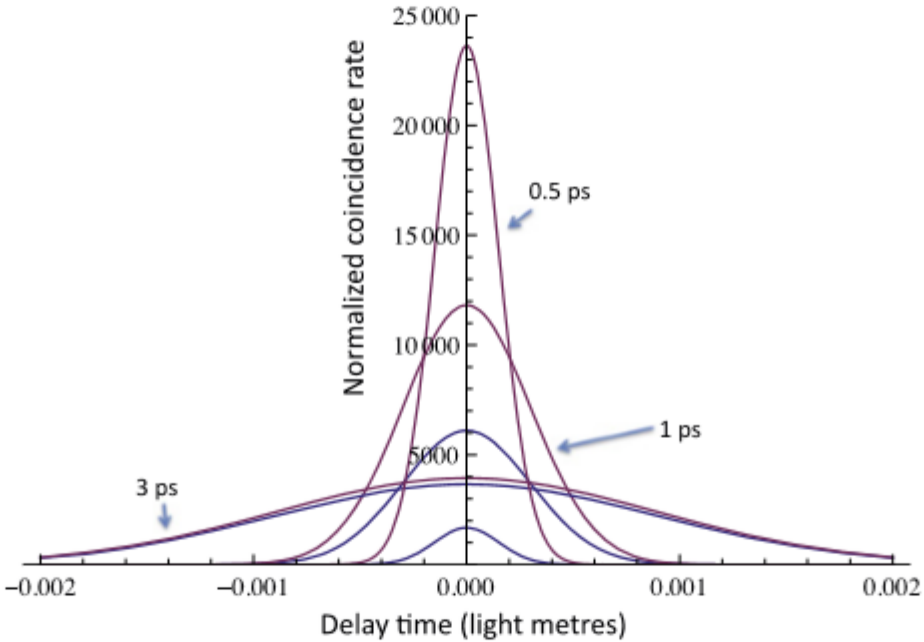
Uncertainty effects[4,5]
Clock precision[6]
Scattering

Gravity?
Other sources?

4. Karolyhazy F, Nuovo Cimento 52 39 (1966)
5. Gambini R, Porto R and Pullin J, Phys. Rev. Lett. 93 240401 (2004)
6. Altepeter, JB, Jeffrey, ER, and Kwiat, PG, Photonic State Tomography
7. Liu, C.L., Zhang, DJ., Yu, XD. et al. Quantum Inf Process 16: 198. (2017)
8. Streltsov, A, et al, Physical Review Letters 115, 020403 (2015)
9. Anastopoulos and B L Hu, Class. Quantum Grav. 30 165007 (2013)

Experimental Setup
Reference 11: Ralph, TC and Pienaar, J, New Journal of Physics, 16 085008 (2014)





Space and time like separated detectors collect entangled particles. The detectors are at different **Gravitational Potential Energies**.

Could there be a measurable de-coherence of the correlation (C) between the two detectors?

Models for Gravity-Induced Quantum Decoherence

Propagate using Hamiltonian containing gravitational and vacuum interactions; treat as linearized perturbations from weak gravitational fields and relative velocity << c

$$\rho_t(p, p') = \exp\left[-\frac{i}{2m_R}(p^2 - p'^2)t - \frac{4\pi G\Theta}{9m_R^2}(p^2 - p'^2)^2 t\right]\rho_0(p, p')$$ [9]

Θ: "textures of spacetime" [9]
The underlying configuration of spacetime – has **not** been measured

Θ: 0 → no decoherence due to gravity; "Minkowski spacetime is the ground state of quantum gravity"
Θ > 0 → "Gravity is a hydrodynamic theory", coarse-grained structure of arbitrary length scale may exist in spacetime

9. Anastopoulos and B L Hu, Class. Quantum Grav. 30 165007 (2013)

Models for Gravity-Induced Decoherence

- Deutsch's theory[10]: curved spacetime may contain closed time like lines
  - A particle can interact with a future version of itself
- Ralph and Pienaar developed framework to measure resultant decoherence sending entangled light 'along the well' in the Schwarzschild metric[11]

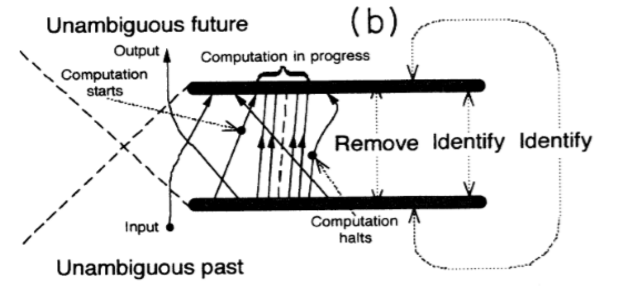
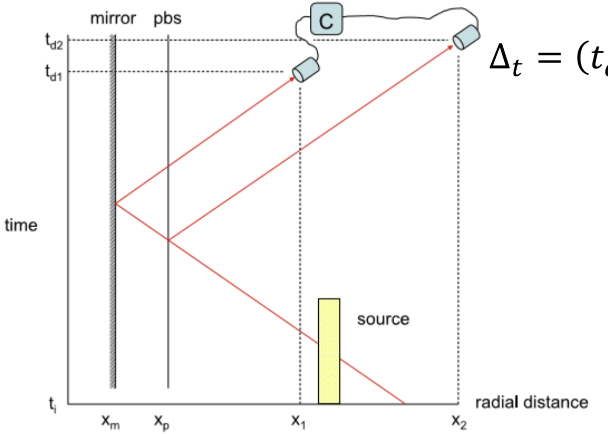


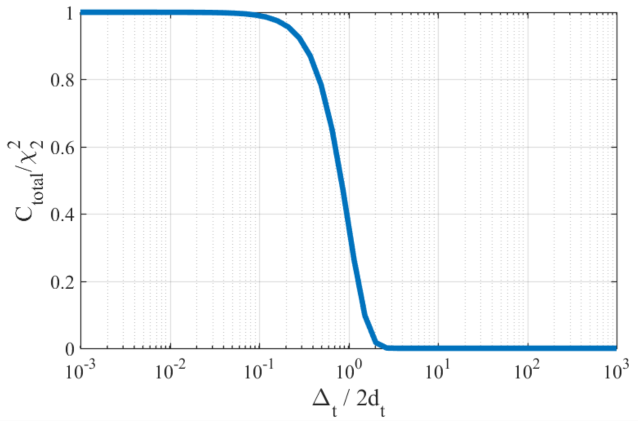
FIG. 7. (a) How to compute anything in no time? (b) Space-time implementation of Fig. 7(a).



$$\Delta_t = (t_{d1} - t_{d2}) + (\tau_2 - \tau_1) \approx M ln({}^{x_1}/_{x_2})$$

$$\tau(t, t_d) = \int_t^{t_d} ds$$

$$C_{\text{total}} = |\chi_2|^2 e^{-\frac{\Delta_t^2}{2d_t^2}}.$$

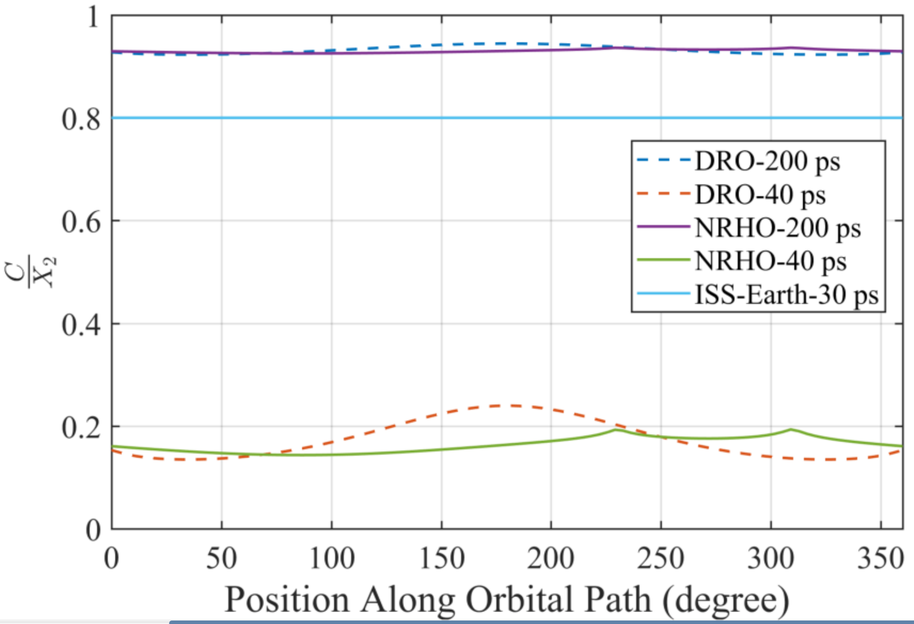


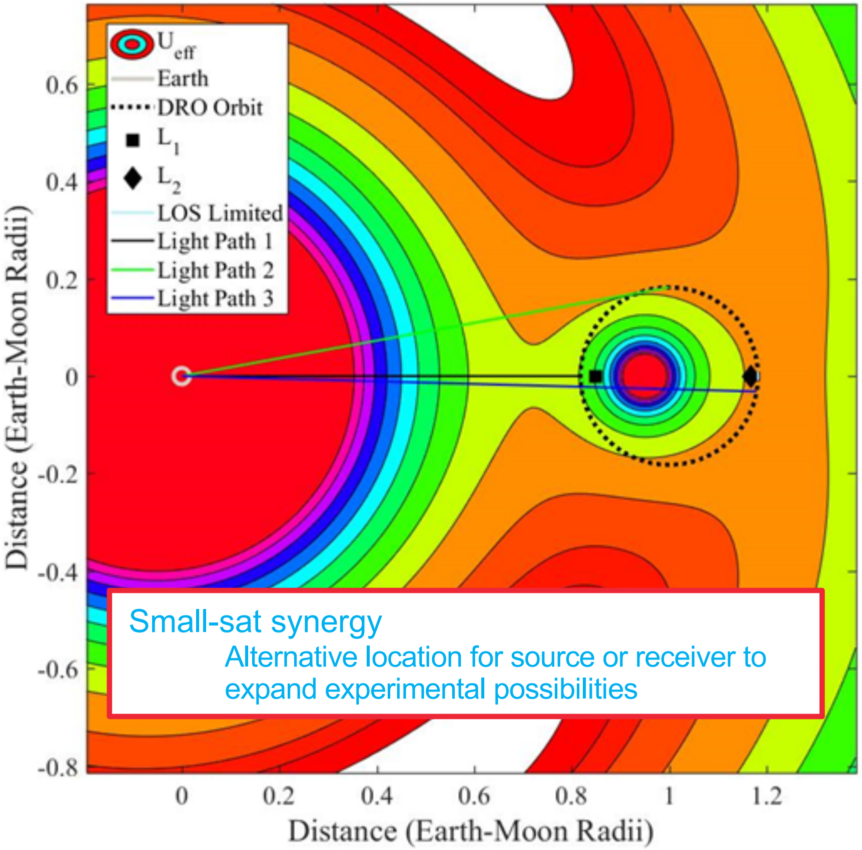
10. Deutsch, D, Physical Review D, 44, 10 (1991)
11. Ralph, TC and Pienaar, J, New Journal of Physics, 16 085008 (2014)

Transitioning from point-like Earth to the N-Body system

First Order Evaluation:

- Linear sum of point-like sources (Earth-Sun-Moon-Jupiter)
- Flying qubit is in its own inertial frame
- An independent test of the Equivalence Principle





Open question: how do points of inflection in the field line of sight affect the mechanism of decoherence?

N-Body System

Next Order Evaluation:

- Rework integration outside of "event formalism" symmetric-shell framework
- N-body numerical solution will have off-diagonal terms
- Potential to test alternative gravity theories
    - Replace earth Schwarzschild radius with n-body effective Schwarzschild radius per PPN[12]

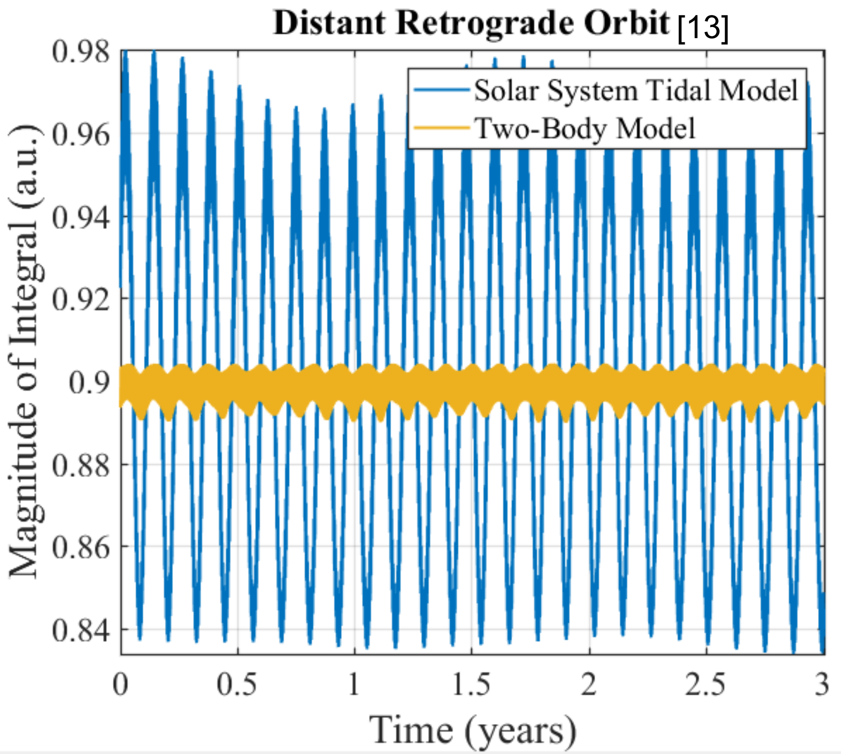
$$\tau(t, t_d) = \int_t^{t_d} ds \qquad ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu,$$

$$g_{00} = 1 - 2\alpha \sum_i \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|} + 2\beta\left(\sum_i \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|}\right)^2 + 2\alpha' \sum_i \sum_{j\neq i} \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|}\frac{m_j}{|\boldsymbol{r}_i-\boldsymbol{r}_j|}$$

$$+\frac{\chi}{c^2}\sum_i \frac{m_i(\boldsymbol{r}-\boldsymbol{r}_i)\cdot\boldsymbol{a}_i}{|\boldsymbol{r}-\boldsymbol{r}_i|} - \frac{4\alpha''}{c^2}\sum_i \frac{m_i v_i^2}{|\boldsymbol{r}-\boldsymbol{r}_i|} + \frac{\alpha'''}{c^2}\sum_i \frac{m_i\{(\boldsymbol{r}-\boldsymbol{r}_i)\cdot\boldsymbol{v}_i\}^2}{|\boldsymbol{r}-\boldsymbol{r}_i|^3}$$

$$g_{0k} = \frac{4\Delta}{c}\sum_i \frac{m_i(\boldsymbol{v}_i)_k}{|\boldsymbol{r}-\boldsymbol{r}_i|} + \frac{4\Delta'}{c}\sum_i \frac{m_i\{(\boldsymbol{r}-\boldsymbol{r}_i)\cdot\boldsymbol{v}_i\}(\boldsymbol{r}-\boldsymbol{r}_i)_k}{|\boldsymbol{r}-\boldsymbol{r}_i|^3}$$

$$g_{kl} = -\left(1 + 2\gamma\sum_i \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|}\right)\delta_{kl},$$



12. B Breen J. Phys. A: Math. Nucl. Gen. 6 150 (1973)
13. https://ssd.jpl.nasa.gov/horizons.cgi

Science Goals

- Place empirical bound on superluminality
  - LOP-G to Earth link can expand bound from ~ 10^6 to 10^{12}
- Test of strong form equivalence principle
  - Preferred orbits of LOP-G exhibit large modulation in angular momentum and gravitational potential energy
- Long range Bell test
  - Eliminate causality loophole in testing
- Probe coupling between gravity and quantum states
  - Test beyond “turning point” from 1-body to N-body spacetime
  - Does spacetime “texture” have sign?
- Crew Interactions
  - Eliminate freedom of choice loophole

System Model for deep space quantum optics

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$$N_r = N_t(\eta_t \eta_r \eta_L \eta_D) \cdot \left(S_{\sigma_X^2} \cdot S_{TB} \cdot S_{Turr} \cdot S_{ext} \cdot S_{BQ} \cdot S_{res.Jit} \cdot S_{HO}\right) \cdot \left(\frac{\Delta F}{\Delta f} \cdot \frac{T}{\omega_r \sigma_y(T)}\right) \cdot (\eta_{eve})$$

Basic Link Budget [14]

- N_r : # Counts/Pulse received
- N_t : # Photons/Pulse at source
- η_t : transmitter gain
- η_r : receiver gain
- η_L : diffraction loss
- η_L : detector efficiency

Strehl Efficiencies [14]

- $S_{\sigma_X^2}$: Propagation turbulence ~ exp(-Rytov^2)
- S_{TB} : Thermal Blooming ~ 1 (<1 for use of bright beacons)
- S_{Turr} : Shear flow around aperture ~ 1 (<1 for airborne)
- S_{ext} : Atmospheric losses ~ exp(-αL)
- S_{BQ} : Loss due to imperfect Beam Quality ~ BQ^{-1}
- $S_{res.jit}$: Pointing jitter of transmitter ~ $[1+\pi/2(\sigma_{jit}/\varphi_{DL})^2]$
- S_{HO} : Finite A.O. loop bandwidth ~ exp(- $(f_g/f_{AO})^{.5}$)

Amount of signal dedicated to circumventing eavesdroppers

Frequency and Time Filtering Efficiencies

- ΔF/Δf: ratio of Rx filter bandwidth to spectral bandwidth of entangled photons
- Product of repetition frequency and Alan variance @ T must be less than T to maintain time synchronization

$$N_{noise} = \left(\frac{\mathcal{W}\Delta F}{E_{photon}} \frac{\lambda^2}{A_{rx}} + N_t \frac{\Delta F}{\Delta f} \cdot ER + T \cdot N_{dark}\right)$$

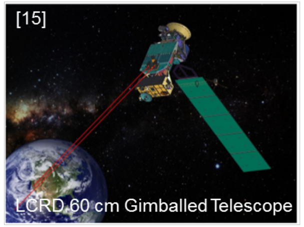
Noise Flux

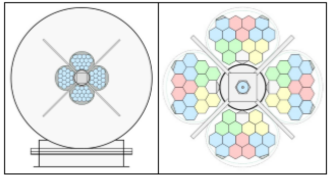
- W : background radiance
- E_{photon} : energy per photon
- A_{rx} : physical area of receiver aperture
- ER : source extinction ratio
- N_{dark} : dark count rate of

Proposed and planned work on small-satellite quantum communication will improve many of these parameters

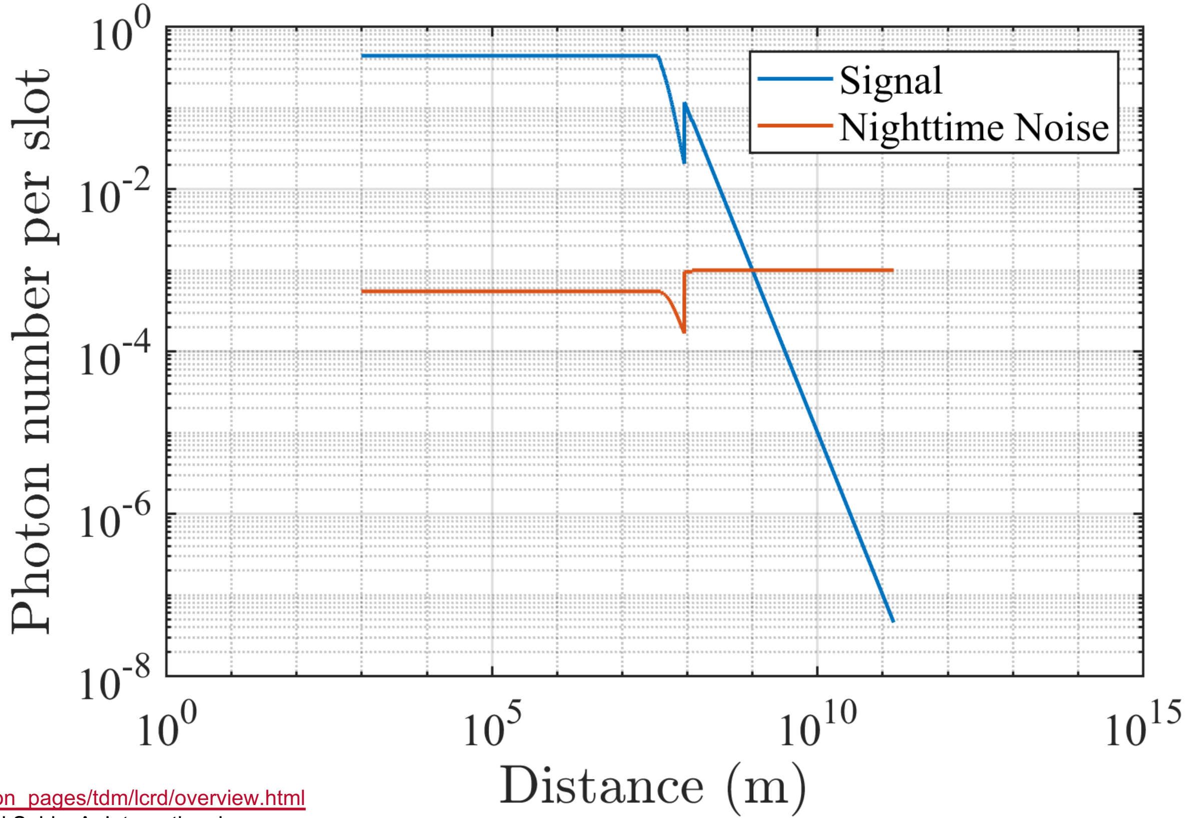
14. Perram et al, Laser Weapon Systems, Chapter 8, DEPS (2010); & Gagliardi & Karp, Optical Communications, 2nd Ed., Wiley (1995)

Basic Link Budget: Maximum Distance for Repeater-Free Quantum Communication to Earth





[16]: JPL large area ground receivers for deep space optical communication



Noise dominates signal at 0.01 AU distance

(mean Earth-Moon Distance ~ .0026AU)

15. arXiv: 1804.06839, https://www.nasa.gov/mission_pages/tdm/lcrd/overview.html
16. Charles, JR, Hoppe, DJ, and Sehic, A; International Conference on Space Optical Systems and Applications (2011)

Time and Frequency Filtering

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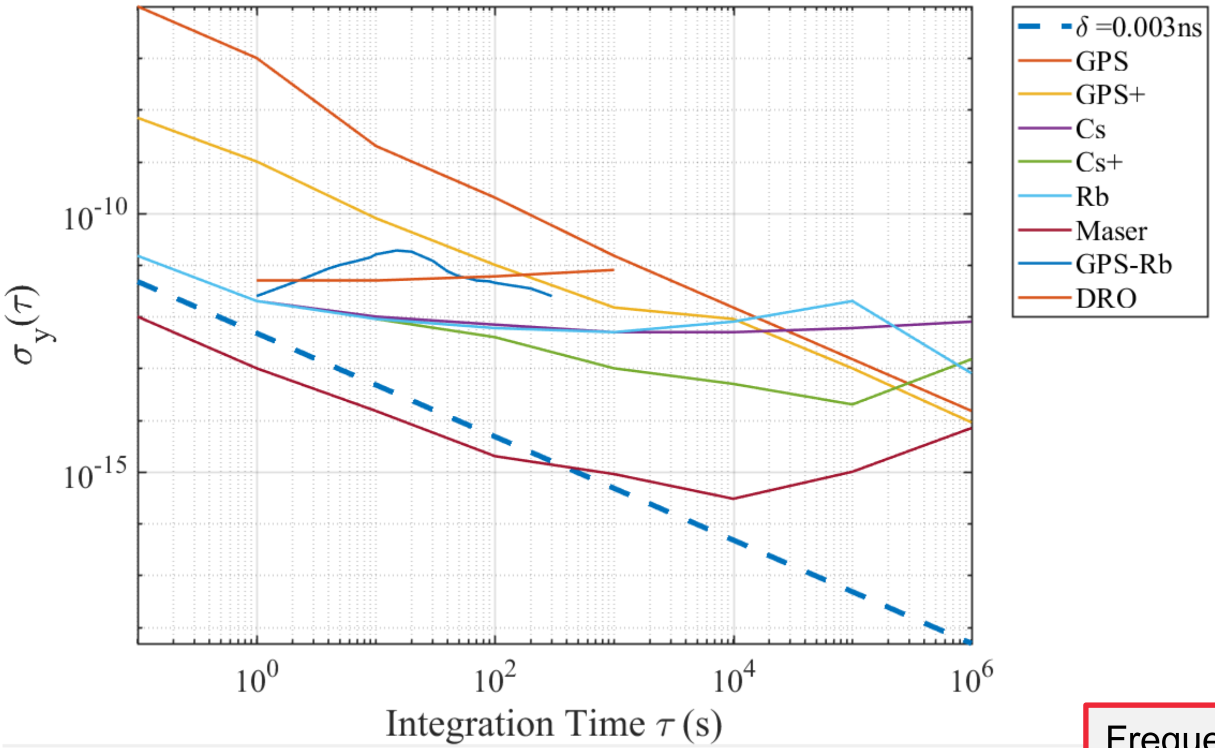
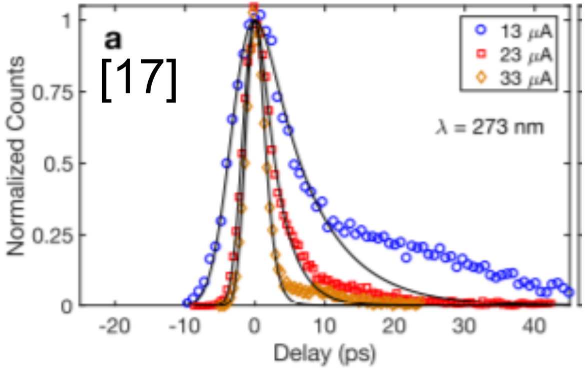


To take advantage of state of the art detectors, precision timing is required to synchronize transmitter and receivers. TWTT or other protocols may be used.



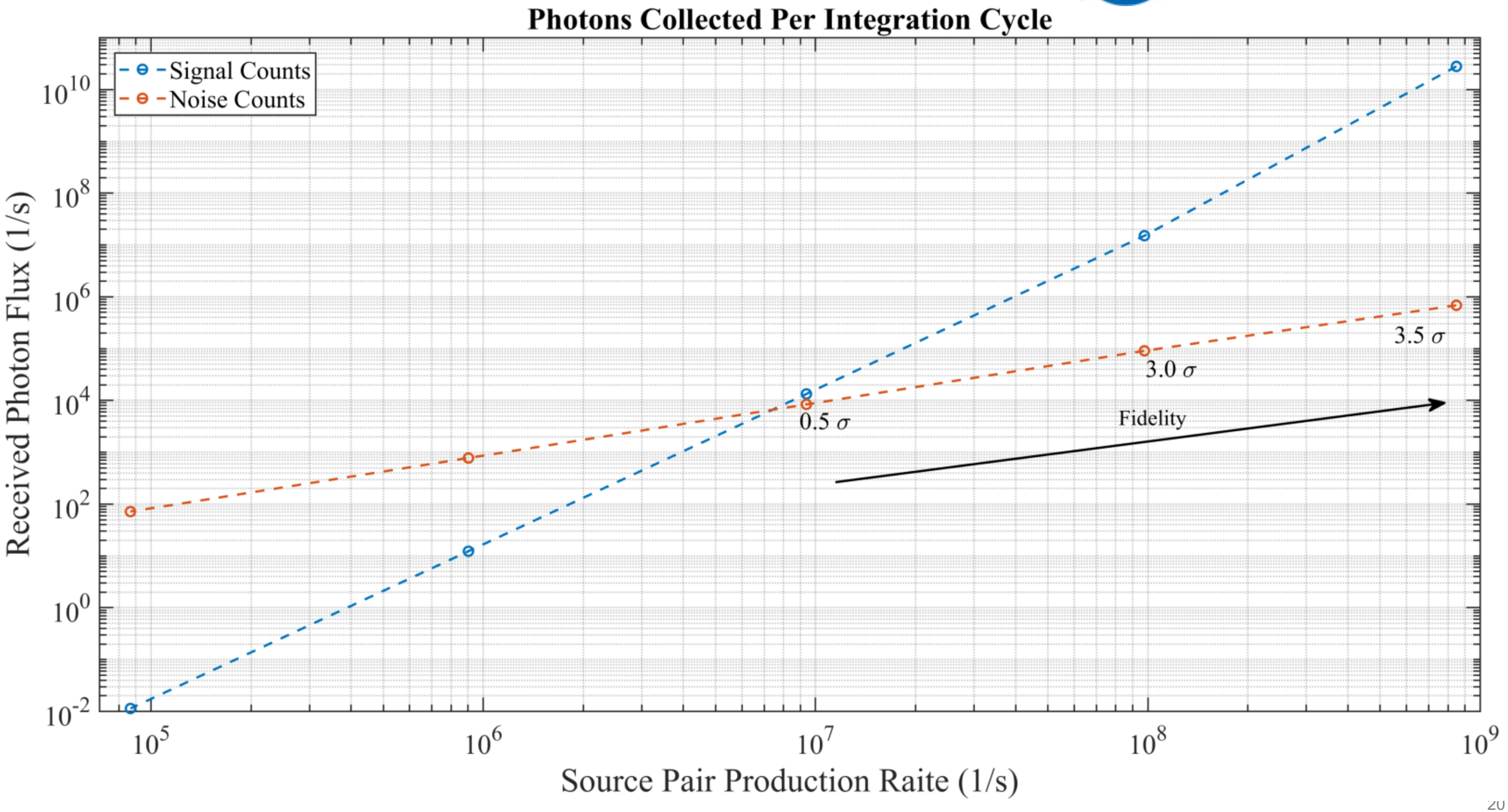
17. arXiv: 1804.06839

Frequency and Bandwidth Constraints

$$\Delta F/\Delta f \leq 1$$

$$2\Delta f \leq f_{rep}$$

Parametric Performance Simulation



Deep Space Quantum Link

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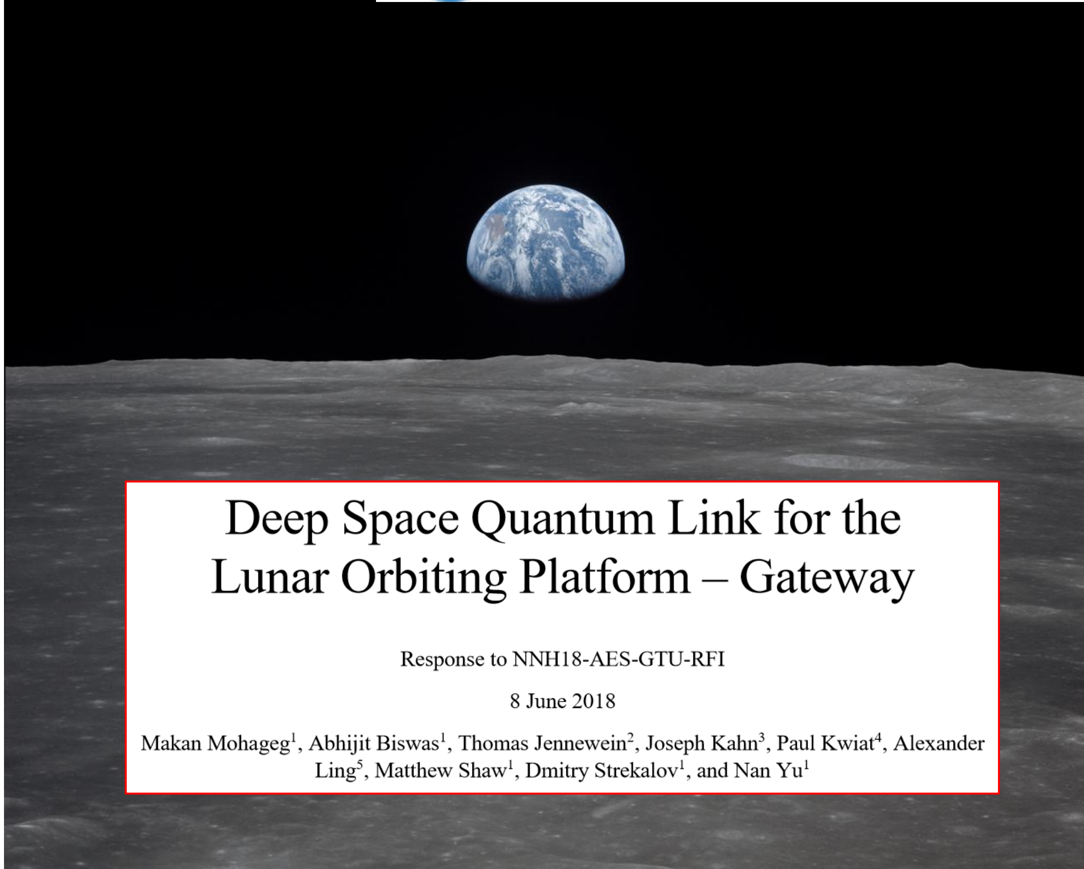
- We do not know if quantum coherence is coupled to gravity
- We do not know if there is fine structure or texture in curved spacetime
- We do not know if time forms closed loops in the presence of mass
- We do not know if wavefunction collapse is 'faster' than 10^6 x speed of light [19]
- **Addressing these questions experimentally will open new doors for fundamental physics, and influence the practical design of planned quantum communication networks and satellite links**

- Earth-orbiting missions to distribute entangled photon pairs to two different gravitational potentials could validate existence of this type of coupling
- **Moon-orbiting missions will unambiguously determine the detailed nature of the coupling; test the equivalence principle; and potentially test alternative metric theories**



Deep Space Quantum Link for the Lunar Orbiting Platform – Gateway

Response to NNH18-AES-GTU-RFI

8 June 2018

Makan Mohageg[1], Abhijit Biswas[1], Thomas Jennewein[2], Joseph Kahn[3], Paul Kwiat[4], Alexander Ling[5], Matthew Shaw[1], Dmitry Strekalov[1], and Nan Yu[1]

[18]

18. https://images.nasa.gov/details-as11-44-6551.html
19. B. Cocciaro, J. Phys: Conf Ser. **626** 012054 (2015)

References

LOP-G Website: https://www.nasa.gov/mission_pages/tdm/lcrd/overview.html

1. Guo et al, Optica 4 (4) (2017) Yin et al, Science 358 (2017)
2. SPACE QUEST Mission Proposal, arXiv:1703.08036v2 [quant-ph] 26 Apr (2017)
3. Wigner E P, Rev. Mod. Phys. 29 255 (1957)
4. Karolyhazy F, Nuovo Cimento 52 39 (1966)
5. Gambini R, Porto R and Pullin J, Phys. Rev. Lett. 93 240401 (2004)
6. Altepeter, JB, Jeffrey, ER, and Kwiat, PG, Photonic State Tomography
7. Liu, C.L., Zhang, DJ., Yu, XD. et al. Quantum Inf Process 16: 198. (2017)
8. Streltsov, A, et al, Physical Review Letters 115, 020403 (2015)
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12. B Breen J. Phys. A: Math. Nucl. Gen. 6 150 (1973)
13. https://ssd.jpl.nasa.gov/horizons.cgi
14. Perram et al, Laser Weapon Systems, Chapter 8, DEPS (2010); Gagliardi & Karp, Optical Communications 2nd Ed., Wiley (1995)
15. arXiv: 1804.06839, https://www.nasa.gov/mission_pages/tdm/lcrd/overview.html
16. Charles, JR, Hoppe, DJ, and Sehic, A; International Conference on Space Optical Systems and Applications (2011)
17. arXiv: 1804.06839
18. https://images.nasa.gov/details-as11-44-6551.html
19. B. Cocciaro, J. Phys: Conf Ser. **626** 012054 (2015)

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